

HYDRODYNAMIC TRANSPORT AND FLOW CHANNEL PASSAGEWAYS
ASSOCIATED WITH FUEL CELL ELECTRODE STRUCTURES
AND FUEL CELL ELECTRODE STACK ASSEMBLIES

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application is a continuation-in-part of U.S. Patent Application
No. 09/715,830 filed November 17, 2000; which application claims priority to
U.S. Provisional Patent Application No. 60/200,866 filed May 2, 2000; U.S. Provisional
Patent Application No. 60/189,205 filed March 14, 2000; and U.S. Provisional Patent
Application No. 60/166,372 filed November 17, 1999; all of which are incorporated
10 herein by reference in their entireties. This application also claims the benefit of
priority of U.S. Patent Application No. 09/839,787 entitled "Metallic Blocking Layers
Integrally Associated With Fuel Cell Electrode Structures and Fuel Cell Stack
Assemblies"; U.S. Patent Application No. 09/839,786 entitled "Silicon-Based Fuel Cell
Electrode Structures and Fuel Cell Electrode Stack Assemblies"; and U.S. Patent
15 Application No. 09/839,950 entitled "Sol-Gel Derived Fuel Cell Electrode Structures
and Fuel Cell Electrode Stack Assemblies"; all of which were filed on April 19, 2001
and are all also incorporated herein by reference in their entireties.

TECHNICAL FIELD

20 The present invention relates generally to fuel cell systems and, more
specifically, to (1) hydrodynamic transport and flow channel passage structures
associated with fuel cell electrode structures and fuel cell electrode stack assemblies
and (2) direct reactant/electrolyte liquid feed fuel cell systems.

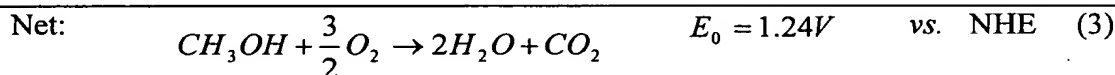
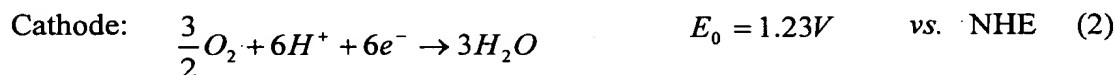
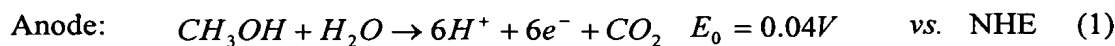
BACKGROUND OF THE INVENTION

25 A fuel cell is an energy conversion device that consists essentially of two
opposing electrodes, an anode and a cathode, ionically connected together via an
interposing electrolyte. Unlike a battery, fuel cell reactants are supplied externally
rather than internally. Fuel cells operate by converting fuels, such as hydrogen or a
hydrocarbon (*e.g.*, methanol), to electrical power through an electrochemical process

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rather than combustion. It does so by harnessing the electrons released from controlled oxidation-reduction reactions occurring on the surface of a catalyst. A fuel cell system can produce electricity continuously so long as fuel is supplied from an outside source.

In electrochemical fuel cell systems employing methanol as the fuel supplied to the anode (also commonly referred to as a “Direct Methanol Fuel Cell” (DMFC) system), the electrochemical reactions are essentially as follows: first, a methanol molecule’s carbon-hydrogen, and oxygen-hydrogen bonds are broken to generate electrons and protons; simultaneously, a water molecule’s oxygen-hydrogen bond is also broken to generate an additional electron and proton. The carbon from the methanol and the oxygen from the water combine to form carbon dioxide. Oxygen from air (supplied to the cathode) is likewise simultaneously reduced at the cathode. The ions (protons) formed at the anode migrate through the interposing electrolyte and combine with the oxygen at the cathode to form water. From a molecular perspective, the electrochemical reactions occurring within a direct methanol fuel cell (DMFC) system are as follows:



The various electrochemical reactions associated with other state-of-the-art fuel cell systems (e.g., hydrogen or carbonaceous fuel) are likewise well known to those of ordinary skill in the art of fuel cell technologies.

With respect to state-of-the-art fuel cell systems generally, several different configurations and structures have been contemplated - most of which are still undergoing further research and development. In this regard, existing fuel cell systems are typically classified based on one or more criteria, such as, for example, (1) the type of fuel and/or oxidant used by the system, (2) the type of electrolyte used in the electrode stack assembly, (3) the steady-state operating temperature of the electrode

stack assembly, (4) whether the fuel is processed outside (external reforming) or inside (internal reforming) the electrode stack assembly, and (5) whether the reactants are fed to the cells by internal manifolds (direct feed) or external manifolds (indirect feed). In general, however, it is perhaps most customary to classify existing fuel cell systems by the type of electrolyte (*i.e.*, ion conducting media) employed within the electrode stack assembly. Accordingly, most state-of-the-art fuel cell systems have been classified into one of the following known groups:

1. Alkaline fuel cells (*e.g.*, electrolyte is KOH);
2. Acid fuel cells (*e.g.*, electrolyte is phosphoric acid);
3. Molten carbonate fuel cells (*e.g.*, electrolyte is 63% Li_2CO_3 /37% K_2CO_3);
4. Solid oxide fuel cells (*e.g.*, electrolyte is yttria-stabilized zirconia);
5. Proton or ion exchange membrane fuel cells (*e.g.*, electrolyte is NAFION).

Although these state-of-the-art fuel cell systems are known to have many diverse structural and operational characteristics, such conventional systems nevertheless share common characteristics with respect to their reactant delivery and reaction product removal systems. More specifically, conventional state-of-the-art fuel cell systems have fluid transport and channel structures designed to predominantly transport reactants (*i.e.*, a fuel and/or oxidant) via "passive diffusion" to the diffusion boundary layer associated with a catalytic film/layer that has been deposited on an electrode (positive or negative) structure. As is appreciated by those skilled in the art, the catalytic film/layer associated with conventional fuel cell electrodes is a substantially planar region where the electrochemical oxidation-reduction reactions between chemical species occur, and the diffusion boundary layer is the region very close to the electrode surface where, due to side-wall frictional forces, flow velocity tends to zero and mass transport by convection is necessarily negligible. In general, conventional fluid transport and channel structures that rely predominantly on a passive diffusion transport mechanism provide less than optimal mass transfer kinetics, especially in the context of direct liquid feed fuel cells.

As is appreciated by those skilled in the art, mass transfer in a electrochemical fuel cell (*i.e.*, the movement of material from one location to another) arises from differences in electrical and/or chemical potentials at separate locations, and/or from movement of a volume element of a fluid (gas or liquid). Accordingly, the modes of mass transfer are generally understood to be as follows: (1) migration, or the movement of a charged particle under the influence of an electric field such as an electrical potential gradient; (2) diffusion, or the movement of a species under the influence of a gradient of chemical potential such as a concentration gradient, and (3) convection, or fluid flow that occurs because of natural convection (*i.e.*, convection caused by density gradients) and/or because of forced convection (*i.e.*, convection caused by hydrodynamic transport). All three modes of mass transfer may be present, to varying degrees, within existing electrochemical fuel cell systems.

As is further appreciated by those skilled in the art, most conventional DMFC systems generally consist of, among other things, a series of membrane electrodes assemblies (MEAs) configured into a stack, wherein each individual MEA further consists of a two opposing electrodes each having catalytic "active" regions. During operation, the catalytic active regions of such conventional MEAs are exposed, either directly or indirectly, to an adjacently flowing fluid stream (contained within an adjacently positioned fluid removal or delivery flow channel). Importantly, because the catalytic active regions of conventional fuel cell systems are substantially planar in character (*e.g.*, a carbon-fiber sheet or layer having affixed or embedded catalyst particles), and because such active regions are positioned adjacent to a flowing fluid during operation (*e.g.*, a fluid flowing in one or more parallel grooves machined into a graphite or aluminum block), the mass transport of reactants (especially gaseous reactants) to the outer boundary of the diffusion layer of the catalytically active electrode surface is predominantly "diffusion" mass transfer. Stated somewhat differently, incoming reactant fuel must laterally diffuse from diverse locations within a non-catalytically active porous region in order to reach a thin catalytically active proton exchange layer; byproducts of reaction must then laterally diffuse away from the proton exchange layer as they are simultaneously axially convected toward the outlet channel.

For purposes of illustration, simplified drawings of two different diffusional fluid transport regimes associated with two different state-of-the art flow field designs (*i.e.*, standard and interdigitated) have been provided as prior art Figures 1A and 1B, respectively. For purposes of example, at higher current densities, the poor performance characteristics of conventional DMFC systems have been attributed to diffusion mass transfer limitations associated with fuel and oxidant delivery. cite?

In addition to the foregoing, several different configurations and structures have been contemplated for direct liquid feed fuel cell systems such as, for example, a direct methanol electrode structure having a solid polymer electrolyte (SPE).

Because such polymer electrolytes are typically cast as solid membranes, this type of electrode assembly is commonly referred to as a "membrane electrode assembly" (MEA). A typical MEA consists essentially of a proton conducting membrane (*i.e.*, the solid polymer electrolyte) sandwiched between two platinum coated electrode structures. A significant problem, however, with DMFC systems having MEAs is a phenomenon known as "methanol cross-over." As is depicted in prior art Figure 2, methanol in conventional DMFC systems has a tendency to cross-over from the anode to the cathode via diffusion (*i.e.*, it migrates through the electrolyte), where it adsorbs onto the cathode catalyst and reacts with oxygen from air resulting in a parasitic loss of methanol fuel and concomitant reduction in fuel cell voltage. Indeed, performance losses of 40-100 mV at a given current density have been observed at the cathode of DMFC systems utilizing a direct methanol feed (Potje-Kamloth et al., *Abstract No. 105, Extended Abstracts 92-2*, "Fall Meeting of the Electrochemical Society" (1992), Kuver et al., *J. Power Sources* 52:77 (1994)).

Conventional attempts for reducing methanol cross-over in DMFC systems having MEAs include structural modifications of the central solid polymer membrane. Exemplary in this regard are the MEAs disclosed in (1) U.S. Patent No. 4,664,761 to Zupancic *et al.* (discloses proton-conducting membrane made of an interpenetrating polymer network); (2) U.S. Patent No. 5,672,438 to Banarjee *et al.* (discloses proton-conducting laminated membrane); and (3) U.S. Patent No. 5,919,583 to Grot *et al.* (discloses proton-conducting membrane that includes an inorganic filler).

Although the various MEA designs disclosed in these patents are able to reduce methanol cross-over to some degree, they nevertheless still have relatively high methanol permeabilities.

Other attempts for reducing methanol cross-over include the incorporation of a metallic barrier layer into the electrode assembly. Exemplary in this regard are the metal hydride barrier layers disclosed in (1) Pu *et al.*, "A Methanol Impermeable Proton Conducting Composite Electrolyte System," *J. Electrochem. Soc.*, 142(7):119-120 (July 1995) (discloses a three-layered laminar electrolyte consisting of a palladium foil layer sandwiched between two polymeric electrolytes); (2) U.S. Patent No. 5,759,712 to Hockaday (discloses a semi-permeable plastic electrode structure having a top palladium membrane that contains numerous swellable voids); and (3) U.S. Patent No. 5,846,669 to Smotkin *et al.* (discloses a hybrid electrolyte system consisting of an acid electrolyte, a base electrolyte, and an interposing palladium foil layer). Although the various MEA designs disclosed in these patents are better able to reduce methanol cross-over than other conventional designs, they too are also less than optimal because of problems caused by the poor ability of such foils to tolerate mechanical stresses (from hydration cycling effects). In short, these state-of-the-art hydrogen permeable metallic blocking layers are known to experience significant problems with cracking and/or delamination.

Although significant progress has been made with respect to these and other fuel cell system problems, there is still a need in the art for improved fluid transport and flow channel passageways associated with fuel cell electrode structures and fuel cell electrode stack assemblies, as well as improved direct liquid feed fuel cell systems. The present invention fulfills these needs and provides for further related advantages.

SUMMARY OF THE INVENTION

In brief, the present invention relates generally to fuel cell systems and, more specifically, to hydrodynamic transport and flow channel passage structures associated with fuel cell electrode structures and fuel cell electrode stack assemblies, as

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well as to methods relating thereto. In one embodiment, the present invention is directed to a fluid delivery and removal channel passage structure integrally associated with an electrode structure (*e.g.*, anode) of a fuel cell system. The fluid delivery and removal channel passage structure comprises: a fluid delivery channel disposed across
5 a first face of the electrode structure; a fluid removal channel disposed across a second face of the electrode structure, wherein the second face opposes the first face; and a porous bulk matrix fluid transport layer interposed between the fluid delivery channel and the fluid removal channel, wherein the porous bulk matrix fluid transport layer is adapted to hydrodynamically flow a gas or liquid therethrough, and wherein the porous
10 bulk matrix fluid transport layer is in fluid communication with the fluid delivery and the fluid removal channels.

In another embodiment, the present invention is directed to a fluid delivery and removal channel passage structure associated with an electrode structure (*e.g.*, cathode) of a fuel cell system, characterized in that the fluid delivery and removal
15 passage structure comprises an inlet passage and an outlet passage separated by a porous bulk matrix fluid transport layer, wherein the porous bulk matrix fluid transport layer is adapted to hydrodynamically flow a gas or liquid therethrough, and wherein the porous bulk matrix fluid transport layer is in fluid communication with the inlet passage and the outlet passage.

In still another embodiment, the present invention is directed to a fluid transport passageway structure integrally associated and in combination with a bi-polar electrode plate assembly of a fuel cell system, characterized in that bi-polar electrode plate assembly comprises an anodic electrode structure bonded together with an opposing cathodic electrode structure. In this embodiment, the anodic electrode
20 structure comprises: one or more anodic fluid delivery channels positioned on a first side of the anodic electrode structure; one or more anodic fluid removal channels positioned on a second side of the anodic electrode structure, wherein the second side is substantially parallel to the first side of the anodic electrode structure; and one or more porous bulk matrix anodic fluid transport regions, wherein each porous bulk matrix
25 anodic fluid transport region is positioned in between at least (i) one of the one or more
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anodic fluid delivery channels, and (ii) one of the one or more anodic fluid removal channels, and wherein each porous bulk matrix anodic fluid transport region is in fluidic communication with at least one of the one or more anodic fluid delivery channels and at least one of the one or more anodic fluid removal channels. Moreover, and in this
5 embodiment, the cathodic electrode assembly comprises at least one porous bulk matrix cathodic fluid transport region in fluidic communication with an inlet passage and an outlet passage, wherein the porous bulk matrix cathodic fluid transport region is adapted to hydrodynamically flow a gas or liquid therethrough, and wherein the porous bulk cathodic matrix fluid transport region is in fluid communication with the inlet
10 passage and the outlet passage.

The present invention also relates to metallic blocking layers integrally associated with fuel cell electrode structures and fuel cell electrode stack assemblies, as well as to methods relating thereto. In one embodiment, the present invention is directed to a metallic blocking layer integrally associated with an electrode structure of
15 a fuel cell system such as, for example, a direct methanol fuel cell system. In this embodiment, the invention may be characterized in that the electrode structure comprises an inorganic (*i.e.*, noncarbonaceous) support substrate having one or more discrete porous regions, wherein the one or more discrete porous regions is defined by an array of acicular pores disposed across the top surface area of the electrode structure
20 such that at least a portion of the blocking layer covers the top surface area and protrudes into the array of acicular pores. The blocking layer is preferably a substantially voidless metallic membrane that is substantially impermeable to at least methanol and is substantially permeable to hydrogen atoms.

In yet another embodiment, the present invention is directed to an
25 electrode assembly adapted for use with a fuel cell system. In this embodiment, the electrode assembly comprises an anode and an opposing cathode. More specifically, the cathode includes one or more discrete cathode porous regions, wherein the one or more discrete cathode porous regions is defined by an array of interconnected acicular pores, and wherein a top surface of the cathode has thereon a metallic blocking layer
30 defined by a metallic membrane that is substantially impermeable to at least methanol

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and is substantially permeable to hydrogen atoms. In contrast, the anode includes one or more discrete anode porous regions, wherein the one or more discrete anode porous regions is defined by an array of anodic acicular pores. The anode and the cathode are spaced apart and substantially parallel to each other so as to define a spaced apart region that is adjacent to the metallic blocking layer. The spaced apart region may also be adapted to flow therethrough an electrolyte/reactant fluid stream.

In yet another embodiment, the present invention is directed to a metallic blocking layer in combination with an inorganic electrode structure of a fuel cell system. In this embodiment, the inorganic electrode structure comprises a bulk matrix having a plurality of acicular pores that extend into the bulk matrix from a top surface. The metallic blocking layer resides on the top surface and partially extends into the plurality of acicular pores. The metallic blocking layer may comprise or consist essentially of a central transition metal diffusion layer (such as, for example, vanadium) having palladium reaction layers on either side.

The present invention also further relates to silicon electrode structures and silicon electrode assemblies associated with fuel cell systems, as well as to methods relating thereto. In one embodiment, the present invention is directed to an electrode structure adapted for use with a fuel cell system such as, for example, a direct methanol fuel cell system. In this embodiment, the invention may be characterized in that the electrode structure comprises a silicon substrate having one or more selectively doped regions thereon, wherein each of the one or more selectively doped regions is adapted to function as a current collector for the transmission of an electrical current.

In another embodiment, the present invention is directed to an electrode structure that comprises a silicon substrate having one or more discrete porous bulk matrix regions disposed across a top surface, wherein each of the one or more discrete bulk matrix porous regions is defined by a plurality of pores that extend into the silicon substrate, wherein the plurality of pores define inner pore surfaces, and wherein the inner pores surfaces have catalyst particles uniformly dispersed thereon. The inner pore surface may also have thereon an interposing layer of ruthenium dioxide (*i.e.*, silicon /

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ruthenium dioxide layer / catalyst particles). In such embodiments, the ruthenium dioxide layer facilitates electron transport away from electrochemical active sites.

The present invention still further relates to sol-gel derived electrode structures and sol-gel derived electrode assemblies associated with fuel cell systems, as well as to methods relating thereto. In one embodiment, the present invention is directed to an electrode structure adapted for use with a fuel cell system such as, for example, a direct methanol fuel cell system. In this embodiment, the invention may be characterized in that the electrode structure comprises a support substrate or structure having a one or more discrete porous regions, wherein each of the one or more discrete porous regions comprise a sol-gel. The sol-gel of the present invention may comprise platinum ruthenium dioxide, platinum-ruthenium-silicon oxide, platinum-ruthenium-titanium oxide, platinum-ruthenium-zirconium oxide, platinum-ruthenium-aluminum oxide, or a combination thereof; preferably, however, the sol-gel comprises platinum ruthenium dioxide.

In still yet another embodiment, the present invention is directed to a fuel cell system that comprises: a porous anode structure; a porous cathode structure; and a liquid fuel and electrolyte mixture that ionically connects the anode to the cathode; wherein the anode structure and the cathode structure are spaced apart and substantially parallel to each other so as to define a spaced apart region, and wherein the liquid fuel and electrolyte mixture is interposed between the anode structure and the cathode structure and within the spaced apart region, and wherein the porous anode structure is in fluid communication with the spaced apart region and is adapted to flow the liquid fuel and electrolyte mixture therethrough, and wherein the porous anode structure has inner pore surfaces that have (i) a catalyst uniformly deposited thereon, and (ii) a polymeric catalyst uniformly deposited thereon.

These and other aspects of the present invention will become more evident upon reference to following detailed description and attached drawings. It is to be understood, however, that various changes, alterations, and substitutions may be made to the disclosure contained herein without departing from the spirit and scope of the present invention. It is to be further understood that the drawings are illustrative

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(hence, not necessarily to scale) and symbolic representations of exemplary embodiments of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A illustrates diffusional fluid transport within a flow channel structure of a prior art MEA.

Figure 1B illustrates diffusional fluid transport within an interdigitated flow channel structure of a prior art MEA.

Figure 2 illustrates a schematic representation of a prior art membrane electrode assembly associated with a direct methanol fuel cell system.

Figure 3 illustrates a top isometric view of a hydrodynamic transport passageway structure integrally associated with an anode structure of a fuel cell system in accordance with an embodiment of the present invention.

Figure 4 illustrates a top isometric view of a hydrodynamic transport passageway structure integrally associated with a cathode structure of a fuel cell system in accordance with an embodiment of the present invention.

Figure 5 illustrates a top exploded isometric view of a hydrodynamic transport structure integrally associated with an electrode assembly of a fuel cell system in accordance with an embodiment of the present invention.

Figure 6 illustrates a top isometric view of the hydrodynamic transport structure integrally associated with the electrode assembly of Figure 5.

Figure 7 illustrates a side cross-sectional view taken along line 7-7 of the hydrodynamic transport structure of Figure 6.

Figure 8 illustrates a side cross-sectional view taken along line 8-8 of the hydrodynamic transport structure of Figure 6.

Figure 9 illustrates an exploded top isometric view of fluid transport and flow channel passageways associated with a fuel cell electrode stack assembly in accordance with an embodiment of the present invention.

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Figures 10A and 10B illustrate magnified top views of a porous silicon substrate having an array of acicular pores useful as a support substrate in accordance with an embodiment of the present invention.

Figure 11 illustrates a magnified side view of a porous silicon substrate
5 having an array of acicular pores useful as a support substrate in accordance with an embodiment of the present invention.

Figure 12 illustrates a further magnified side view of the porous silicon of Figure 11.

Figure 13 illustrates a magnified side view of a porous silicon substrate
10 useful as a support substrate in accordance with an embodiment of the present invention.

Figure 14 illustrates a magnified side view of a porous "Kielovite" silicon substrate useful as a support substrate in accordance with an embodiment of the present invention.

Figure 15 illustrates a magnified side view of a porous silicon substrate
15 useful as a support substrate in accordance with an embodiment of the present invention.

Figure 16 illustrates a magnified view of a silicon substrate having a plurality of catalyst particles uniformly dispersed thereon in accordance with an
20 embodiment of the present invention.

Figure 17 shows a side cross-sectional view of a porous silicon electrode having thereon a palladium blocking layer in accordance with an embodiment of the present invention.

Figures 18A-C show top and side cross-sectional views of a silicon
25 anode structure in accordance with an embodiment of the present invention.

Figures 19A-C show bottom and side cross-sectional views of a silicon anode structure in accordance with an embodiment of the present invention.

Figures 20A-B show top and bottom views of a silicon cathode structure in accordance with an embodiment of the present invention.

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Figure 21 shows a side cross-sectional of a silicon cathode structure in accordance with an embodiment of the present invention.

Figures 22A-D top and side cross-sectional views of a sol-gel derived cathode structure in accordance with an embodiment of the present invention.

5 Figures 23-52 illustrate sequential side cross-sectional views of a silicon substrate that has been subjected to various process steps in accordance with an embodiment of the present invention.

Figures 53A and 53B illustrates top isometric views of a silicon anode structure in accordance with an embodiment of the present invention.

10 Figures 54-79 illustrate sequential side cross-sectional views of a silicon substrate that has been subjected to various process steps in accordance with an embodiment of the present invention.

Figures 80A, 80B and 80C illustrates top isometric views of a silicon cathode structure in accordance with an embodiment of the present invention.

15 Figures 81-127 illustrate sequential side cross-sectional views of a silicon substrate that has been subjected to various process steps to form a sol-gel derived anode structure in accordance with an embodiment of the present invention.

Figures 128-163 illustrate sequential side cross-sectional views of a silicon substrate that has been subjected to various process steps to form a sol-gel derived cathode structure in accordance with an embodiment of the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

In a first aspect, the present invention is directed to hydrodynamic transport and flow channel passage structures integrally associated with fuel cell electrode structures and fuel cell electrode stack assemblies, as well as to methods relating thereto. The novel hydrodynamic transport and flow channel passage structures disclosed herein advantageously allows reactants and/or oxidants to reach the diffusion layer of the catalytic active regions of fuel cell electrode structures predominantly by a forced convection mass transfer mechanism (as opposed to a diffusion mass transfer mechanism), which is achieved by flowing a fluid reactant/electrolyte (1) through a

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catalytically active bulk matrix (*i.e.*, a volumetric region of the fuel cell electrode where the electrochemical oxidation-reduction reactions between chemical species take place) and (2) immediately adjacent to both the anode structure and cathode structure of an electrode assembly (both of which comprise a polymeric electrolyte coating on their respective pore surfaces). In such a configuration, the flowing fluid reactant/electrolyte ionically connects the anode structure to the cathode structure. In the context of the present invention, suitable fluid reactant/electrolytes include, for example, an organic liquid fuel combined with an acid solution (*i.e.*, a liquid aprotic organic electrolyte). Exemplary organic fuels comprise water and an alcohol such as ethanol, propanol, methanol, or a combination thereof; and the acid solution may be phosphoric acid, sulfuric acid, trifluoromethane sulfonic acid, or a combination thereof. In some embodiments, the fluid reactant/electrolyte may be equal molar amounts of methanol and water together with an acid in an amount of about 0.01 to 3.0 M, and preferably in an amount of about 0.25 M.

15 In view of the foregoing and in one embodiment, the present invention is directed to a hydrodynamic transport passageway structure integrally associated and in combination with an electrode structure of a fuel cell system. In other embodiments, the present invention is directed to a fluid delivery and removal channel passage structures associated with an electrode assembly of a fuel cell system. In general, the novel fluid passage structures of the present invention comprise a porous bulk matrix fluid transport layer that is defined by a substrate having an array of interconnected linear acicular pores. In still other embodiments, the present invention is directed to various electrode stack assemblies and fuel cell systems having novel fluidic transport and flow channel passageways. Although these and other specific details of certain embodiments of the present invention are set forth in the following detailed description and accompanying drawings, those skilled in the art will recognize that the invention may have additional embodiments, or that the invention may be practiced without several of the details described herein.

25 Thus, and with reference to Figures 3-8, the present invention is directed to a fluid delivery and removal channel passage structure integrally associated with an

electrode structure 12 of a fuel cell system (not shown) such as, for example, (1) an anode of a bi-polar electrode plate assembly (as best shown in Figure 3), and (2) a cathode of a bi-polar electrode plate assembly (as best shown in Figure 4). As shown in Figure 3, the fluid delivery and removal channel passage structure comprises four fluid delivery channels 14 disposed across a first face 16 of the electrode structure 12. The fluid delivery channels 14 each preferably have dimensions of 10,000 μm (L) x 1,000 μm (W) x 100 μm (T). As shown in Figure 4, the fluid delivery and removal channel passage structure comprises an inlet port 28 and an outlet port 30 separated by a single porous bulk matrix fluid transport layer 32, wherein the porous bulk matrix fluid transport layer 32 is preferably defined by an array of interconnected linear acicular pores, and wherein the inlet and outlet ports 28, 30 are each adapted to transport fluid in a direction perpendicular to the longitudinal axes of the acicular pores. The porous bulk matrix fluid transport layer 32 preferably has dimensions of 10,000 μm (L) x 10,000 μm (W) x 100 μm (T).

As best illustrated in Figure 7 and Figure 8, the fluid delivery and removal channel passage structure also comprises at least one fluid removal channel 18 disposed across a second face 20 of the electrode structure 12 (wherein the second face parallelly opposes the first face). The fluid removal channel 18 preferably has dimensions of 10,000 μm (L) x 10,000 μm (W) x 100 μm (T). The fluid removal channel 18 communicates with each of the fluid delivery channels 14 by way of four interposing porous bulk matrix fluid transport layers 22. The four interposing porous bulk matrix fluid transport layers 22 may be, for example, (1) an array of interconnecting linear acicular pores formed by selective anodic polarization of a silicon wafer in hydrofluoric acid (as described in further detail below), and/or (2) an interconnecting porous matrix structure formed by the selective growth of a metal oxo polymer (as also described in further detail below).

Preferably, however, the bulk matrix fluid transport layers of the present invention comprise interconnecting linear acicular pores, wherein each of the interconnected linear acicular pores are perpendicularly aligned with respect to each of the four fluid delivery channels 14 and the single fluid removal channel 18. In this

configuration, the porous bulk matrix fluid transport layers 22 are each adapted to hydrodynamically flow a gas or liquid therethrough; hence, they are understood to be in fluid communication with each respective fluid delivery channel 14 and the fluid removal channel 18.

5 In addition to the above-disclosed fluid delivery and removal channel structures (integrally associated with fuel cell electrode structures), the present invention is also directed to fuel cell electrode assemblies that comprise an anode structure in combination with a cathode structure, wherein such a configuration allows a flowing reactant/oxidant/electrolyte fluid to ionically connect the anode to the cathode.

10 Accordingly, the present invention is further directed to a fluid transport passageway structure integrally associated and in combination with a bi-polar electrode plate assembly of a fuel cell system. The fluid transport passageway structure may be characterized in that the bi-polar electrode plate assembly comprises an anodic electrode structure bonded together with an opposing cathodic electrode structure (best

15 illustrated in Figures 5 and 6).

In such a bi-polar plate assembly embodiment, the anodic electrode structure preferably comprises: (i) one or more anodic fluid delivery channels 14 positioned on a first side 16 of the anodic electrode structure 12; (ii) one or more anodic fluid removal channels (hidden) positioned on a second side of the anodic electrode structure, wherein the second side is substantially parallel to the first side of the anodic electrode structure; and (iii) one or more porous bulk matrix anodic fluid transport regions 22, wherein each porous bulk matrix anodic fluid transport region 22 is positioned in between at least (a) one of the one or more anodic fluid delivery channels 14, and (b) one of the one or more cathodic fluid removal channels (hidden), and

20 wherein each porous bulk matrix anodic fluid transport region 22 is in fluidic communication with at least one of the one or more anodic fluid delivery channels 14 and at least one of the one or more anodic fluid removal channels (hidden). In contrast, the cathodic electrode structure 24 comprises at least one porous bulk matrix cathodic fluid transport region (not shown) in fluidic communication with an inlet passage and

25 an outlet passage (not shown).

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The present invention is still further directed (as best shown in Figure 9) to fluid transport and flow channel passageway structures 70 associated with a fuel cell electrode stack assembly 72 (shown in exploded view). In this embodiment, the fuel cell electrode stack assembly comprises: (i) a first end cap assembly having a first fluid inlet port and second fluid outlet port; (ii) a second end cap assembly having a third fluid inlet port and a fourth fluid outlet port; and (iii) a plurality of bi-polar electrode plate assemblies interposed between the first and second end cap assemblies, wherein each of the bi-polar plate assemblies comprises an anodic electrode structure bonded together with an opposing cathodic electrode structure.

In the several embodiments set forth herein, the inventive hydrodynamic transport and flow channel passage structures are based, in large part, on novel substrates and support structures that are particularly useful for carrying a catalyst within a bulk fluid flow-through matrix. In this regard, the substrates and support structures disclosed herein principally include silicon substrates, sol-gel derived support structures, and combinations thereof. In particular, it has been discovered that these types of substrates and/or support structures are useful as electrode structures for a fuel cell system (especially for micro-scale direct methanol fuel cell system), mainly because such substrates and/or support structures are able to provide a high surface area to bulk volume ratio, have good mechanical strength, are compatible with thin/thick films which are often needed for making selected electrical connections, and are amenable to the formation of various flow channel structures. Because of these physical characteristics, among others, and because such substrates and/or support structures are also amenable to semiconductor micro-fabrication techniques, the (1) direct liquid feed fuel cell systems and (2) hydrodynamic transport and flow channel passage structures of the present invention may be manufactured by micromachining fabrication techniques associated with integrated circuit (IC) and semiconductor processing..

Accordingly, and without limitation to any particular methodology, the novel channel and porous flow-through regions associated with the electrode structures disclosed herein may be made by utilizing one or more processing techniques such as,

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for example, alkaline etching, plasma etching, lithography, electroplating, as well as electrochemical pore formation on silicon substrates. In this way, a silicon substrate useful for carrying a catalyst within a bulk fluid flow-through matrix (having one or more fluid delivery/removal channels) may be produced. The bulk fluid flow-through matrix may have any number of pores and pore sizes such as, for example, random and ordered pore arrays - including pore arrays having selected pore diameters, depths, and distances relative to one another. Similarly, the novel sol-gel derived support structures may be made by conventional sol-gel processing techniques, wherein the sol-gel derived support structures may have any number of pores, pore sizes, and/or pore structures. In short, the present invention is inclusive of all silicon substrates and sol-gel derived support structures, including combinations thereof, that have any number of possible porosities and/or void spaces associated therewith (as long as such structures allow for hydrodynamic fluid transport).

In view of the foregoing, an aspect of the present invention relates to the use of a silicon substrate (*e.g.*, a silicon wafer) as a support structure for carrying a catalyst, wherein the silicon substrate together with the catalyst serves as a flow-through hydrodynamic electrode structure (*e.g.*, a porous bulk matrix fluid transport layer or region) of a fuel cell system. Thus, and in one aspect, the present invention is directed to a silicon-based electrode structure having integrally associated therewith a fluid delivery and removal passage structure. In this regard, porous silicon substrates (and/or support structures) may be formed by silicon micro-machining and/or wet chemical techniques (employed by the semiconductor industry) such as, for example, anodic polarization of silicon in hydrofluoric acid. As is appreciated by those skilled in the art of silicon anodic etching, the anodic polarization of silicon in hydrofluoric acid (HF) is a chemical dissolution technique and is generally referred to as HF anodic etching; this technique has been used in the semiconductor industry for wafer thinning, polishing, and the manufacture of porous silicon films that a wide variety of thicknesses. (*See, e.g.*, Eijkel, et al., "A New Technology for Micromachining of Silicon: Dopant Selective HF Anodic Etching for the Realization of Low-Doped Monocrystalline Silicon Structures," *IEEE Electron Device Ltrs.*, 11(12):588-589

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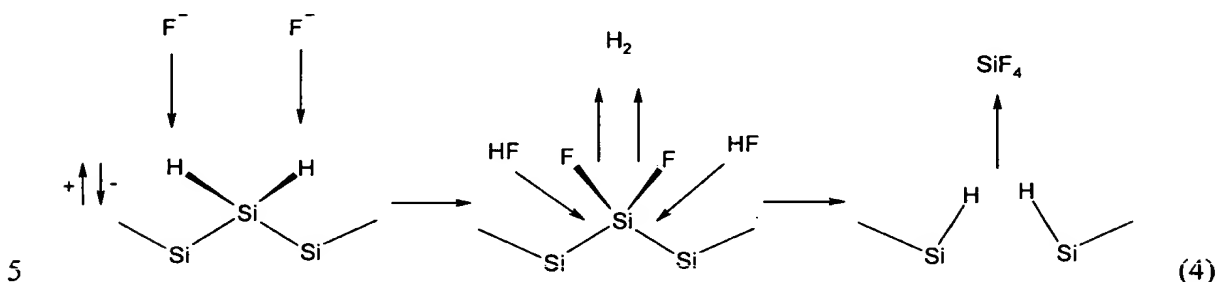
(1990)). Accordingly, and based on these methods, an aspect of the present invention relates to forming a porous silicon having an engineered morphology. In the context of the present invention, it is to be understood that the porous silicon layer may be nanoporous silicon (*i.e.*, average pore size < 2 nm), mesoporous silicon (*i.e.*, average pore size of 2 nm to 50 nm), or macroporous silicon (*i.e.*, average pore size > 50 nm).

More specifically, porous silicon substrates useful in the context of the present invention may be formed by a photoelectrochemical HF anodic etching technique, wherein selected oxidation-dissolution of silicon occurs under a controlled current density. (See, *e.g.*, Levy-Clement et al., "Porous n-silicon Produced by Photoelectrochemical Etching," *Applied Surface Science*, 65/66:408-414 (1993); M.J. Eddowes, "Photoelectrochemical Etching of Three-Dimensional Structures in Silicon," *J. of Electrochem. Soc.*, 137(11):3514-3516 (1990).) An advantage of this relatively more sophisticated technique over others is that it is largely independent of the different principal crystallographic planes associated with single-crystal silicon wafers (whereas most anisotropic wet chemical etching methods have differences in rates of etching along the different principal crystallographic planes). The photo-electrochemical HF anodic etching of n-type silicon, for example, depends upon, among other things, the existence of holes (h^+) at or near the silicon surface/solution interface. As is appreciated by those skilled in the art of silicon anodic etching, such holes may be generated by illumination of the silicon surface (n-type); and the holes' transport or flux to the silicon/solution interface may be controlled by an applied potential bias (together with its associated electric field). Once at or near the silicon/solution interface, the photo-generated holes may take part in oxidation-reduction reactions with surface atoms. In a suitable electrolyte HF solution, oxidation-reduction will be followed by dissolution of the oxidation product such that etching will proceed. (Note that for p-type silicon, holes are readily available so there is generally no need for photo-illumination.)

Several chemical oxidation-dissolution models have been reported to explain the reaction mechanism that occurs during the electrochemical HF anodic etching of silicon. Perhaps, the most popular model is the one proposed by Lehmann

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and Gosele. (Lehmann et al., "Porous Silicon Formation: A Quantum Wire Effect," *Applied Physics Letter*, 58(8)856-858 (1991)). The mechanism proposed by Lehmann and Gosele is schematically depicted below in chemical equation (4).



According to the Lehmann and Gosele model as represented by chemical equation (4), silicon, when immersed in a HF solution, will form a Si-H bond on the surface. The holes and their transport to or near the silicon surface/solution interface (caused by supplying a voltage together UV illumination for n-type silicon) reduces the strength of the Si-H bonds thereby allowing formation of Si-F₂, which, in turn, results in a weakening of the Si-Si bonds. Hydrofluoric acid from the solution then causes the weakened Si-Si bond to break, thereby causing the formation of SiF₄, which, in turn, goes into the surrounding solution.

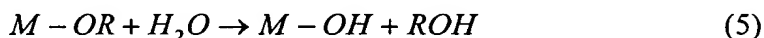
15 In order to form porous silicon substrates by a photoelectrochemical HF anodic etching technique as described above, it is necessary to either obtain or construct an anodic etching cell. In this regard, a suitable anodic etching cell may be obtained commercially from Advanced Micromachining Tools GmbH (Frankenthal, Germany); alternatively, an appropriate anodic etching cell may be constructed.

20 For purposes of enhanced clarity and conceptualization, Figures 10-15 show various porous silicon substrates that are useful for supporting a catalyst thereon and/or for flowing a fluid reactant/electrolyte therethrough (*e.g.*, through a bulk fluid flow-through matrix) in accordance with certain embodiments of the present invention.

25 As previously noted, another aspect of the present invention relates to the use of a sol-gel derived support structure that is optionally carrying a catalyst, wherein the sol-gel derived support structure together with the optional catalyst serves as a flow-through hydrodynamic electrode of a fuel cell system. Thus, and in one

aspect, the present invention is directed to a sol-gel derived electrode structure (optionally integrated together with a silicon substrate) having integrally associated therewith a fluid delivery and removal passage structure. As is appreciated by those skilled in the art of sol-gel chemistry, sol-gel processes are a way to make dispersed ceramic materials through the growth of metal oxo polymers in a solvent. (see, e.g., Brinker et al., "Sol-Gel Science, the Physics and Chemistry of Sol-Gel Processing," *Academic* (1990).) The chemistry associated with sol-gel processes is based on inorganic polymerization reactions. In this regard, metal oxo polymers useful in the context of the present invention may be obtained through hydrolysis and condensation of molecular precursors such as metal alkoxides $M(OR)_Z$ (wherein $M =$ Si, Ti, Al, Zr, V, W, Ir, Mn, Mo, Re, Rh, Nb, Ni, Sr, Ba, Ta, Mg, Co; OR is an alkoxy group and Z is the valence or oxidation state of the metal) (Sanchez et al., "Inorganic and Organometallic Polymers with Special Properties," *Nato ASI Series* (Laine R. M., Ed.), 206:267 (1992)).

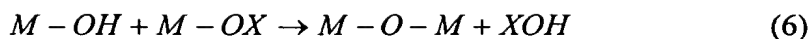
The metal oxo polymerization reaction proceeds first through the hydroxylation of metal alkoxides, which occurs upon the hydrolysis of alkoxy groups as follows:



The mechanism occurs in three steps: (a) nucleophilic attack of the metal M by the oxygen atom of a water molecule; (b) transfer of a proton from the water to an OR group of the metal; and (c) release of the resulting ROH molecule (Livage et al., "Sol-Gel Chemistry of Transition-Metal Oxides," *Progress in Solid State Chemistry*, 18(4):259-341 (1988)).

As soon as reactive hydroxy groups are generated, the formation of branched oligomers and polymers with a metal oxo based skeleton and reactive residual hydroxo and alkoxy groups occurs through a polycondensation process. Depending on experimental conditions, two competitive mechanisms have been described, namely, oxolation and olation.

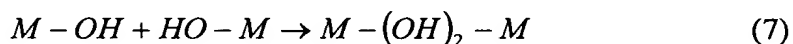
Oxolation involves the formation of oxygen bridges as follows:



(X = H or alkyl group)

5 As with hydrolysis, oxolation is a three step nucleophilic substitution reaction which occurs through the elimination of H₂O or ROH. Generally, under a stoichiometric hydrolysis ratio ($h = H_2O/M < 2$) the alcohol producing condensation is favored, whereas the water forming condensation is favored for larger hydrolysis ratio ($h \gg 2$) (Brinker et al., "Sol-Gel Science, the Physics and Chemistry of Sol-Gel
10 Processing," *Academic* (1990)).

Olation, on the other hand, involves the formation of hydroxo bridges as follows:



15 Olation is a nucleophilic addition reaction that can take place when the coordination of the metallic center is not fully satisfied ($N - Z > 0$). The hydroxo nucleophilic group enters the unsaturated coordination sphere of the metal. This reaction does not need the proton transfer described above (step b) and the removal of a
20 leaving group (step c). Consequently, the kinetics of olation are usually faster than those of oxolation because steps b and c are not necessary (Sanchez et al., "Inorganic and Organometallic Polymers with Special Properties," *Nato ASI Series* (Laine R. M., Ed.), 206:267 (1992)).

In accordance with an aspect of the present invention, these three
25 reactions (hydrolysis, oxolation and olation) may all be involved in the transformation of a metal alkoxide precursor into a metal oxo macromolecular network, where such a metal oxo macromolecular network is referred to herein as a sol-gel derived support structure. The exact structure and morphology of such a sol-gel derived support structure generally depends on the relative contribution of each of these reactions.

30 In exemplary embodiments of the present invention, a sol-gel derived support structure may be cast into etched or micromachined trenches, channels, and/or pits of a silicon substrate (e.g., a silicon wafer with selectively placed trenches),

wherein the sol-gel derived support structure combined with the silicon substrate (together with the catalyst) serves as an electrode structure of a fuel cell system. In this context, exemplary sol recipes (chemicals are commercially available from Aldrich Chemical Company, Inc., Milwaukee, Wisconsin) useful in the practice of the present invention are as follows:

Pt-RuO₂

A platinum-ruthenium oxide precursor solution may be prepared by mixing dihydrogen hexahydroxyplatinate (IV) (H₂Pt(OH)₆), ruthenium(III) 2-4pentanedionate Ru(C₅H₇O₂)₃ with nitric acid (HNO₃), ethyl alcohol (C₂H₅OH), and de-ionized water. The solution may be refluxed under vigorous stirring at ~ 70°C for ~ 2 hrs to yield a nominal molar ratio of 1 : 0.5 : 5 : 5 : 0.5 of: Ru(C₅H₇O₂)₃ : H₂Pt(OH)₆ : H₂O : C₂H₅OH : HNO₃.

Pt - RuO₂ - SiO₂

A platinum-ruthenium-silicon oxide precursor solution may be prepared by first mixing hexachloroplatinic acid (H₂PtCl₆ xH₂O), ruthenium chloride hydrate (RuCl₃ xH₂O) and tetraethoxysilane (Si(OC₂H₅)₄) in ethyl alcohol (C₂H₅OH). A solution of ammonium hydroxide (NH₄OH) and de-ionized water may then added to the refluxing mixture under vigorous stirring at ~ 70°C for ~ 2 hrs to yield a nominal molar ratio of 1 : 0.2 : 0.5 : 5 : 5 : 0.8 of RuCl₃ xH₂O : Si(OC₂H₅)₄ : H₂PtCl₆ xH₂O : H₂O : C₂H₅OH : NH₄OH.

Pt - RuO₂ - TiO₂

A platinum-ruthenium-silicon oxide precursor solution may be prepared by first mixing dihydrogen hexahydroxyplatinate (IV) (H₂Pt(OH)₆) and ruthenium (III) 2-4pentanedionate Ru(C₅H₇O₂)₃ in ethyl alcohol, refluxed and stirred at ~ 70°C for 3 hrs. Separately, titanium (IV) isopropoxide (Ti[OCH(CH₃)₂]₄) may also mixed with ethyl alcohol (C₂H₅OH), refluxed and stirred at ~ 70°C for 3 hrs. Next, the two solutions may be mixed together, refluxed under stirring at ~ 70°C for 3 hrs. Lastly, a

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solution of nitric acid (HNO_3) and de-ionized water may be added to the mixture, refluxed and stirred at $\sim 70^\circ\text{C}$ for ~ 2 hrs to yield a nominal molar ratio of 1 : 0.2 : 0.5 : 5 : 5 : 0.5 of $\text{Ru}(\text{C}_5\text{H}_7\text{O}_2)_3$: $\text{Ti}[\text{OCH}(\text{CH}_3)_2]_4$: $\text{H}_2\text{Pt}(\text{OH})_6$: H_2O : $\text{C}_2\text{H}_5\text{OH}$: HNO_3 .

5 Analogous to the porous silicon support structures, the sol-gel derived support structures of the present invention may also have variable pore sizes and pore morphologies. For example, the pore size may be selectively adjusted by the incorporation of polystyrene latex particles (*e.g.*, latex beads or microspheres) into the sol precursor solution. The latex particles useful for these purposes generally have
10 average diameters ranging about from 0.05 to 10 μm . In addition, the sol-gel may also have a filler component such as, for example, sub-micron ruthenium oxide particles ranging from about 5 to 80 volume percent. (*see generally*, Velev and Kaler, *Adv. Mater.* 12(7):531-534 (2000); and Kulinowski et al., *Adv. Mater.* 12(11):833-838 (2000)). Moreover, and in accordance with certain preferred embodiments of the
15 present invention, any of the above sols may be cast into etched or micromachined trenches, channels, and/or pits of a silicon wafer, and more preferably, into an etched region of a porous silicon substrate. It has been found that the pores of a porous silicon substrate facilitates a mechanical interlocking mechanism for anchoring the sol-gel (thereby reducing the risk of delamination).

20 In yet another aspect of the present invention, an additional metallic oxide layer such as, for example, a 5-50 nm layer of ruthenium oxide deposited by chemical vapor deposition, may also improve the adhesion of the sol-gel to the underlying silicon substrate and provide an enhanced pathway for electron transport away from the active region of the electrode structure. Thus, the inner pore surface
25 may have deposited thereon an interposing layer of ruthenium dioxide (*i.e.*, silicon / ruthenium dioxide layer / catalyst particles).

 Still another aspect of the present invention relates to a metallic catalyst carried on a silicon substrate and/or a sol-gel derived support structure, wherein the catalyst facilitates oxidation-reduction reactions of a fuel (*e.g.*, hydrogen or methanol)
30 or an oxidant (*e.g.*, oxygen from air). In this regard, it is to be understood that the

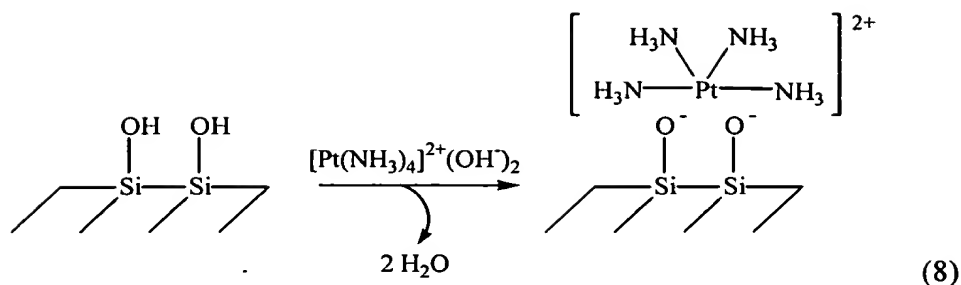
catalyst may be carried on the surface or face of a silicon substrate; and/or the catalyst may be carried on the pore surfaces (*i.e.*, within the bulk matrix of the substrate or support structure) of either a porous silicon substrate or a sol-gel derived support structure (wherein the pore surfaces having catalyst particles thereon are also referred to
5 herein as active regions).

Unlike traditional electrocatalyst deposition methods such as, for example, electroplating, sputtering and metal evaporation (which methods have all been used in conjunction with known fuel cell electrode structures; mainly to form substantially planar catalytic films or layers disposed across an electrode surface), the
10 metallic catalyst aspect contemplates the use of surface organometallic chemistry techniques to form a metallic and/or bi-metallic catalyst dispersion on or within a silicon substrate or sol-gel derived support structure (*i.e.*, the active regions). The formation of such a metallic and/or bi-metallic catalyst particles or noncontiguous layers by the use of surface organometallic chemistry techniques provides for an
15 extremely efficient use of the catalyst (thereby resulting in significant cost savings), and allows for the dispersion of the catalyst throughout the bulk matrix of the substrate and/or support structure (thereby enhancing the oxidation-reactions occurring thereon).

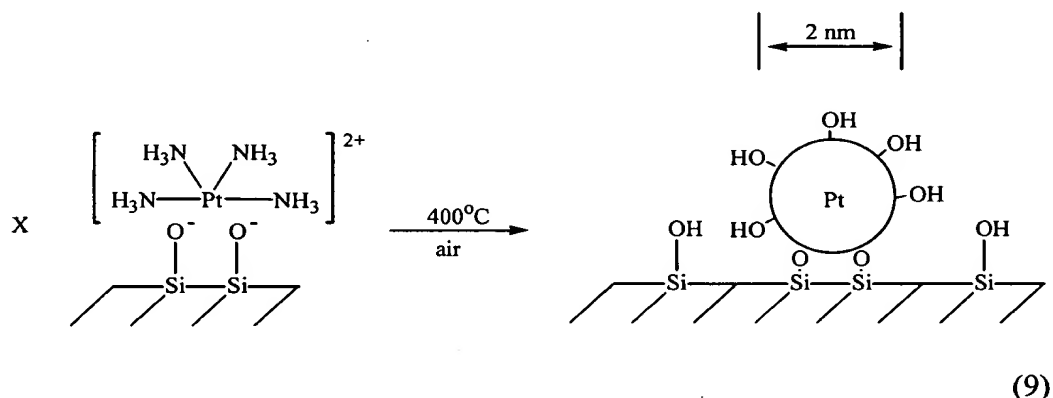
In the context of direct methanol fuel cells, for example, it is known that platinum provides one of the best surfaces for the dissociative adsorption of methanol.
20 However, at potentials required for methanol electrooxidation, the $\text{-C}\equiv\text{O}$ intermediates formed during the complete oxidation process are relatively stable on the surface, and as a result they tend to poison the catalyst by blocking the adsorption sites. This tendency may be avoided, to some extent, by the addition of certain other metal additives so as to decrease the stability of the $\text{-C}\equiv\text{O}$ on the surface (and in so doing, it is
25 believed that such metal additives may facilitate the overall oxidation-reduction process). Thus, several mixed metal catalysts may be used (*i.e.*, combinations of one or more noble metals) and are thus considered to be within the scope of the present invention; however, a bi-metallic platinum:ruthenium catalyst is a particularly active bi-metallic catalyst and is therefore preferred (at least with respect to the anode).

As is appreciated by those skilled in the art of organometallic chemistry, the reaction of selected organometallic precursors with exposed surface atoms is one way to deposit or chemisorb a metallic catalyst. For example, the surface of a silicon substrate (including its pore surfaces) may be oxidized by exposure to air and water vapor at slightly elevated temperatures, thereby causing the surface to be covered with hydroxyl groups (Si-OH). These surface hydroxyl groups are active sites, and therefore may be used as the starting point for chemisorbing catalysts thereon via surface organometallic chemistry techniques. For example, the reaction of selected organometallic precursors with surface hydroxyl groups causes the chemisorption of surface supported molecular analogues thereof, which upon reduction gives rise to chemisorbed metallic nanoparticles having very small size distributions. Such methodologies are amenable to not only silicon surfaces, but are also well suited for deposition onto bulk oxides such as, for example, the various sol-gel derived support structures disclosed herein. For purposes of clarity, the terms "chemisorb" and "chemisorption" are to have meanings as understood by those skilled in the art of organometallic chemistry; and as such, these terms refer to molecules held to a surface by forces of the same general type as those occurring between bound atoms in molecules. Moreover, the heat evolved per mole of chemisorbed material is usually comparable to that evolved in chemical bonding, namely, about 100-500 kJ. (Laidler et al., "Physical Chemistry," *Benjamin/Cummings Publishing Company, Inc.* (1982).).

In an exemplary aspect of the present invention, a noncontiguous bi-metallic layer of platinum and ruthenium may be chemisorbed on and/or within a nonporous/porous silicon substrate by selective use of platinum and ruthenium precursors. For example, a silicon substrate may be immersed, under basic conditions (pH 8.5), into an aqueous ammonia solution of tetraamineplatinum(II) hydroxide hydrate, $[\text{Pt}(\text{NH}_3)_4](\text{OH})_2 \cdot x\text{H}_2\text{O}$, (commercially available from Strem Chemicals, Inc., Newburyport, Maine) and stirred for a selected period of time, thereby causing formation of a platinum complex in accordance with chemical equation (8):



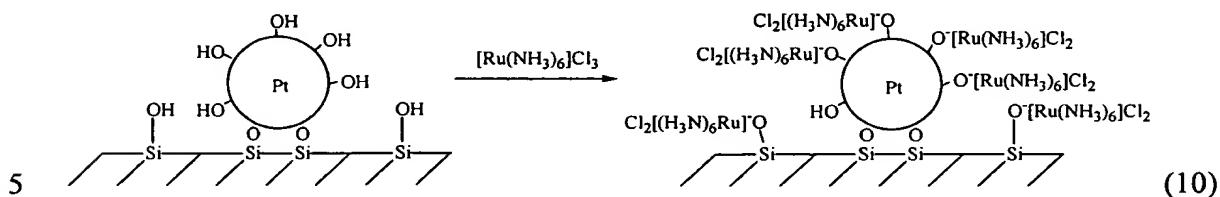
After washing with cold water, the silicon substrate may then be calcined in air to remove the remainder of the ligands from the platinum. This step may be done under a slow temperature ramp, 25-400°C, over a selected period of time, as is shown in chemical equation (9).



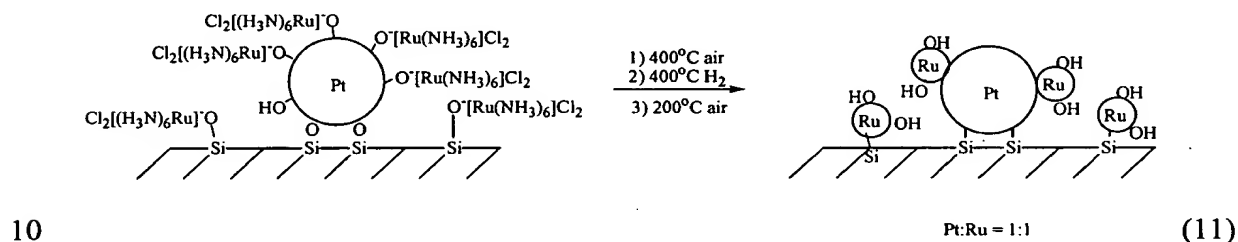
In general, the slower the temperature is increased, the smaller the size of the chemisorbed platinum particles (*i.e.*, greater surface area, and narrower size distribution). (Humblot et al., "Surface Organometallic Chemistry on Metals: Formation of a Stable $\text{Sn}(\text{n-C}_4\text{H}_9)$ Fragment as a Precursor of Surface Alloy Obtained by Stepwise Hydrogenolysis of $\text{Sn}(\text{n-C}_4\text{H}_9)_4$ on a Platinum Particle Supported on Silica," *J. Am. Chem. Soc.*, 120(1):137-146 (1998); and Humblot et al., "Surface Organometallic Chemistry on Metals: Selective Dehydrogenation of Isobutane into Isobutene on Bimetallic Catalysts Prepared by Reaction of Tetra-*n*-Butyltin on Silica-Supported Platinum Catalyst," *J. Catal.*, 179(2):458-468 (1998).).

Next, and after the silicon substrate has reached room temperature, it may then be immersed, under basic conditions (pH 8.5), into an aqueous ammonia solution of hexamineruthenium(III) chloride, $[\text{Ru}(\text{NH}_3)_6]\text{Cl}_3$ (commercially available

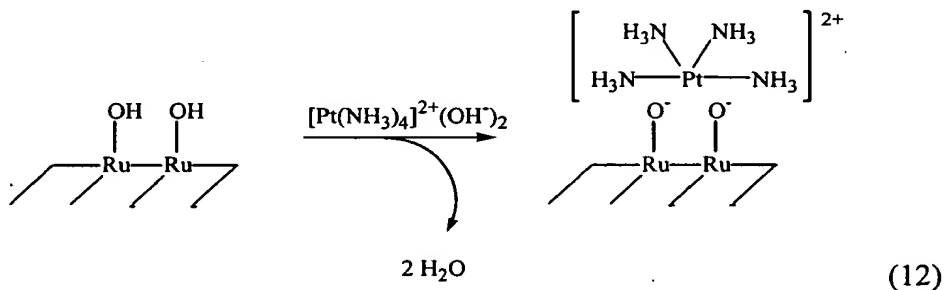
from Strem Chemicals, Inc., Newburyport, Maine), and stirred for a selected period of time, thereby causing formation of a ruthenium complex in accordance with chemical equation (10).



Finally, the catalyst may be reduced under flowing H_2 at $400^\circ C$ (1% in nitrogen) to form a mixed platinum ruthenium catalyst in accordance with chemical equation (11).

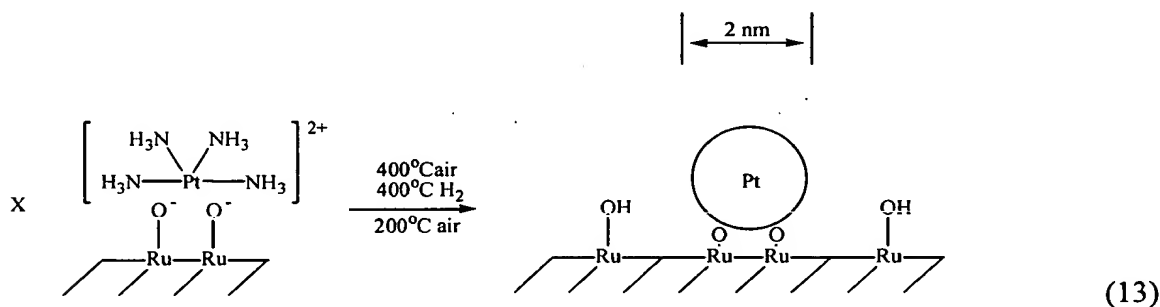


Furthermore, the previously described techniques are not limited to silicon substrates but can also be used for the deposition of catalyst onto the sol-gel derived support structures. For example, a ruthenium dioxide sol-gel substrate can be immersed in an aqueous ammonia solution of tetraamineplatinum(II) hydroxide hydrate as described above resulting in the formation of a surface bound platinum complex, equation (12).



After washing with cold water, the ruthenium dioxide substrate may then be calcined in air to remove the remainder of the ligands from the platinum. This step

may be done under a slow temperature ramp, 25°C to 400°C, over a selected period of time. The catalyst may then be reduced under flowing H₂ at 400°C (1% in nitrogen) to reduce the platinum followed by heating at 200°C in air to ensure the surface of the ruthenium dioxide is fully oxidized, equation (13).



- 10 For purposes of enhanced conceptualization, Figure 16 illustrates a magnified view of a silicon substrate having a plurality of catalyst particles uniformly dispersed thereon in accordance with an embodiment of the present invention.

As noted above, the present invention is also directed to metallic blocking layers integrally associated with fuel cell electrode structures and fuel cell electrode stack assemblies, as well as to methods relating thereto. In these embodiments, the electrode structures of the present invention are characterized in that they are generally made from an inorganic or noncarbonaceous substrate such as, for example, a silicon wafer, a sol-gel derived support structure, or a combination thereof. An important feature of these types of novel inorganic support substrates is that they may be manufactured so as to comprise a plurality of catalytic active porous regions (*i.e.*, volumetric regions within the fuel cell electrode where the electrochemical oxidation-reduction reactions between chemical species take place). These volumetric active porous regions are extremely useful for obtaining relatively high power densities in miniature fuel cell systems, but only to the extent that problems associated with fuel cross-over are obviated. Unlike conventional graphite or plastic electrode support structures, the novel inorganic support substrates disclosed herein (1) are able to form an adhesion or fusion bonding layer (between the metallic blocking layer and the

support substrate) that mitigates problems associated with delamination, and (2) are able to define an array of pores (*e.g.*, a pattern of columns that extends into the inorganic bulk matrix) that provides an expansion route that mitigates problems associated with cracking. These improved physical characteristics are due, in large part, to the crystalline nature of the underlying inorganic substrates and support structures (whereby their crystalline nature makes them particularly amenable to forming fusion bonds with metals).

Thus, and with reference to Figure 18, the present invention is directed to a palladium blocking layer 10 integrally associated with an electrode structure 12 of a fuel cell system (not shown) such as, for example, a DMFC system. In this embodiment, the electrode structure 12 comprises an inorganic (*i.e.*, noncarbonaceous) support substrate 14 having one or more discrete porous regions, wherein the one or more discrete porous regions is defined by an array of acicular pores 16 disposed across the top surface area of the electrode structure 12 such that at least a portion of the blocking layer 10 covers the top surface area and protrudes into the array of acicular pores 16 (note that the pores are preferably interconnected). As shown, the palladium blocking layer 10 is a substantially voidless metallic palladium membrane, and the support substrate 14 is porous silicon (*e.g.*, a bulk silicon matrix having a plurality of acicular pores). Moreover, because of the crystalline nature associated with silicon and palladium, the support substrate 14 may be fusion bonded together with the palladium blocking layer 10 (optionally with an interposing metallic glue layer) such that the opposing crystalline lattices commingle.

Thus, and in view of the foregoing, an aspect of the present invention relates to the use of an inorganic support substrate support structure for carrying a metallic blocking layer thereon. Preferably, the inorganic support substrate is porous silicon, a sol-gel, or a silicon/sol-gel combination.

As further noted above, the inventive metallic blocking layer in combination with a silicon substrate and/or a sol-gel derived support structure, selectively allows for the transport of hydrogen atoms or protons while blocking substantially all other molecules. In particular, this aspect of the invention enjoys

significant utility with respect to preventing “methanol cross-over,” which phenomena commonly occurs in electrode assemblies of DMFC systems (wherein the methanol has a tendency to cross-over from the anode to the cathode). Without necessarily prescribing to any particular scientific theory, the hydrogen ion transport mechanism associated with direct liquid feed cell systems such as, for example, DMFC systems may be stated as follows:

1. Hydrogen ions diffuse via the electrolyte (polymeric or flowing reactant/electrolyte fluid) to the surface of the methanol barrier.

2. The hydrogen ions adsorb to the surface of the methanol barrier.

3. The hydrogen ions gain electrons from the metallic electron cloud and transfers from an adsorbed state on the surface to an absorbed state within the crystalline matrix of the methanol barrier.

4. The hydrogen ions diffuse through the crystalline matrix by jumping from interstitial site to interstitial site in a manner similar to the Brownian diffusion of molecules through a fluid.

5. The hydrogen ions reach the opposite surface, loses electrons to the electron cloud of the metallic film and changes from the absorbed state within the crystalline matrix to the adsorbed state on the surface.

6. The hydrogen ions desorb from the surface of the methanol barrier into the electrolyte (polymeric or flowing reactant/electrolyte fluid).

7. The hydrogen ions diffuse away from the methanol barrier via the electrolyte (polymeric or flowing reactant/electrolyte fluid).

The rate-limiting steps associated with such a transport mechanism are believed to be the electron transfer steps and the bulk diffusion step. In this regard, the diffusion of hydrogen through the crystalline matrix of the metallic blocking layer is referred to as the Bulk Diffusion step. The rate at which hydrogen diffuses through the matrix is largely controlled by the concentration gradient across the membrane, the

thickness of the membrane, and the diffusion coefficient of the membrane as set forth below in the following equation (14):

$$N = \frac{D_T (C_{out} - C_{in})}{\delta} \quad (14)$$

5

wherein

N	Hydrogen flux through the membrane	ccH ₂ /cm ₂ · sec
D _T	Hydrogen diffusivity for a given membrane at a given temperature	cm ₂ /sec
C _{out}	Concentration of hydrogen in the membrane materials on the inlet side of the membrane	ccH ₂ /ccMetal
C _{in}	Concentration of hydrogen in the membrane material on the outlet side of the membrane	ccH ₂ /ccMetal
δ	Thickness of the metal membrane	cm

Accordingly, the greater the concentration difference between the inlet and outlet side of the membrane, the greater the hydrogen flux. In such a blocking system, the concentration at the inlet and outlet are generally affected only by the concentration of hydrogen ions in the electrolyte and the potential difference between electrolyte and membrane. Thus, the thinner the membrane, the greater the hydrogen flux. The diffusivity of the membrane is largely controlled by the membrane's composition and temperature (the diffusivity of the membrane increases with increasing operating temperature). Materials that typically have high rates of bulk diffusion include the noble metal palladium and the transition metals vanadium, niobium and tantalum (all of which are considered to be within the scope of the present invention).

The rate at which the electron transfer step proceeds is related to the total amount of surface area available for the electron transfer to occur, the suitability of the surface for the electron transfer reaction, and the temperature of the surface. (Metals that are particularly fast for electron transfer include platinum and palladium.) The electron transfer reaction generally only occurs at specific locations on the membrane

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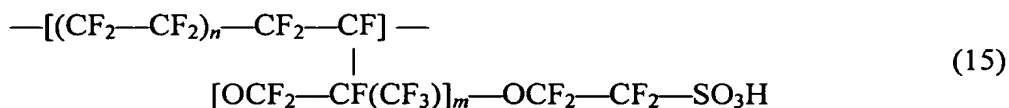
surface. These reactions sites have a set density depending on how the surface of the membrane is prepared. The greater the surface area of the membrane the greater the total number of reactions sites where electron transfer can occur. In order to facilitate the electron transfer reactions, electrons from the metallic membrane need to be readily available. In order for this to occur, the surface of the membrane is preferably a metal with minimal adsorbed contaminants or oxide deposits. In general, increasing the temperature of the reaction system causes an increase of the rate at which the electron transfer reactions occur. In this regard, vanadium, niobium and tantalum all have bulk diffusion rates higher than that of palladium at similar temperatures; however, these metals all readily form layers of tightly bound oxides that greatly inhibit the electron transfer reaction. As a result, and although the bulk diffusion rate is greater in these metals, the actual rate of diffusion through these metals is much lower than a comparable palladium film under the same operating conditions.

In order to incorporate the high diffusion rates and relatively lower cost of the transition metals with the fast electron transfer reaction rate of palladium, a layered membrane structure may be formed in accordance with certain embodiments of the present invention. This structure generally comprises a central transition metal diffusion layer, such as vanadium, together with a thin palladium surface reaction layer on either side. Such a metallic membrane may be either be a solid self-supported metallic film, or it may be partially deposited into a porous matrix (e.g., porous silicon substrates and/or sol-gel derived support structures as disclosed herein).

In the context of the present invention, there are several different methods available for depositing a metallic membrane layer (depending on the material being deposited and the structure of the underlying substrate). In the case of a transition metal foil, no deposition process needs to occur as processing is simply a matter of preparing the surface in such a way so as to enhance the electron transfer reaction. Alternatively, when depositing the metallic layer onto a porous matrix, the metal needs to be deposited in such a way as to ensure intimate contact with the surrounding pore surfaces of the underlying bulk matrix. In this way, delamination and strain effects caused by crystal lattice expansion are minimized by virtue of there being a support

matrix around the metal. Furthermore, because the metal membrane transcends the stretch of the porous cavity, the possibility of buckling of the film is minimized to only deflection when the film experiences the lateral stress induced by swelling of the film during proton (hydrogen) migration since it is supported by the surrounding porous walls. As is appreciated by those skilled in the art, a metallic film of palladium may be deposited on a silicon substrate and/or a sol-gel derived support structure by, for example, electroplating, physical vapor deposition, sputtering, thermal evaporation, e-beam evaporation, and electroless deposition, or a combination thereof.

As also noted above, an aspect of the present invention relates to the use of polymeric electrolytes on the pore surfaces of each electrode structure. In this regard, and in one aspect, the present invention relates to the impregnation of a polymer electrolyte into the porous silicon substrates and/or sol-gel derived support structures having a chemisorbed catalyst thereon so as to optimize the three-phase interface between catalyst, fuel and proton-conducting electrolyte. With respect to the polymer electrolyte associated with the various electrode assemblies disclosed herein, it may be a polymer ion-exchange membrane - generally of an acid type, such as, for example, a perfluorosulfonic acid membrane. Exemplary in this regard, are membranes known as NAFION (E. I. Du Pont de Nemours and Company, United States) which are, in general, electrochemically stable at temperatures up to about 100°C. These membranes have a polytetrafluoroethylene (PTFE) polymer chain as a backbone, several units ($n = 6-10$) in length, with a flexible branch pendant to this chain, a perfluorinated vinyl polyether ($m \geq 1$) with a terminal acidic (sulfonic) group to provide the cation- (proton-) exchange capability. As an example, such an ionomer unit may have the following structure (equivalent weight about 1200):



In general, membranes of this type have a high proton conductivity ($> 2 \Omega^{-1} \cdot \text{cm}^{-2}$); the proton transport number is generally unity with a low electro-osmotic

water transport rate (though the water content may be about 30%). The hydrogen and oxygen permeabilities are generally small: $3\text{-}5 \times 10^{-4} \text{ cm}^3 \cdot \text{cm}/\text{cm}^2 \cdot \text{h} \cdot \text{atm}$ at 25°C . Such a membrane is generally stable against chemical attack in strong bases, strong oxidizing and reducing acids, hydrogen peroxide, chlorine, etc., up to temperatures of 125°C. In the context of the present invention, the polymer electrolyte is preferably a perfluorosulfonic polymer membrane having a thickness ranging from about 20 to 200 microns.

As is appreciated by those skilled in the art, NAFION is available as a 5 weight percent solution in alcohols and water, which when applied to the electrodes disclosed herein may wet the surface and flow into the pores of the active regions. When dry, the polymer tends to stick to the internal surfaces but does not completely fill the channels, so that fuel will be able to infuse the structure and protons will be conducted across the cell. With a coating of the surfaces inside the porous structure, exceptional catalyst utilization and proton transport may be achieved.

For purposes of illustration and not limitation, the following examples more specifically disclose various aspects of the present invention.

EXAMPLES

EXAMPLE 1

SILICON SUBSTRATE ELECTRODES

This example discloses the processing steps associated with making a silicon-based electrode adapted for use with a fuel cell system in accordance with an embodiment of the present invention. In this example, the processing steps consist of (1) the anode fabrication steps, and (2) the cathode fabrication steps. Without limitation, the principal processing steps are set forth below and with reference to Figures 23 to 52 and Figures 54 to 79.

ANODE FABRICATION - Start with a silicon substrate having the following characteristics: 400 μm double side polished, (100) crystal orientation, 0.005 to 0.10 Ω -

cm, n-type, 100 mm diameter (refer to Figure 23), and process in accordance with the following steps:

- 5 1.1 Deposit a 5000 Å +/- 5% layer of silicon dioxide (dielectric) on the front and backside of the silicon substrate via wet thermal oxidation (refer to Figure 24).
- 1.2 Deposit 600 Å +/- 5% of silicon nitride (dielectric) on the front and backside of the silicon substrate via LPCVD nitride deposition (refer to Figure 25).
- 10 1.3 Deposit photoresist patterned from Mask A1-1F on the front side of the silicon substrate – the openings only expose the fuel and oxidant inlet/outlets, the dicing lanes, and the flow channels (refer to Figures 26A and 26B).
- 1.4 RIE both dielectrics on the front side of the silicon substrate (refer to Figure 27).
- 15 1.5 Strip the photoresists from the front side of the silicon substrate (refer to Figure 28).
- 1.6 Deposit photoresist patterned from Mask A1-2B on the backside of the silicon substrate – the openings only expose the fuel and oxidant inlet/outlets, the dicing lanes, and the flow channels (refer to Figures 29A and 29B).
- 20 1.7 RIE both dielectrics from the backside of the silicon substrate (refer to Figure 30).
- 1.8 Strip photoresist from the backside of the silicon substrate (refer to Figure 31).
- 25 1.9 KOH etch 150 µm from the front and backside of the silicon substrate – carve out the fuel and oxidant inlet/outlets, the dicing lanes, and the flow channels (refer to Figure 32).
- 1.10 Sputter 200 Å of Ti-W followed by an additional 5000 Å of Au on the front side of the silicon substrate - for the anodic etching Ohmic contact (refer to Figure 33).

5 1.12 Anodic etch the silicon substrate – creating a 200µm porous silicon layer
(refer to Figure 35).

10 1.14 KOH etch out the porous silicon on the inlet/outlet plus electrical channels from the backside of the silicon substrate (quickly) - remove the porous silicon within the fuel and oxidant inlet/outlets and the dicing lanes (refer to Figure 37).

1.16 Remove the Ohmic contact for anodic etching from the front side of the silicon substrate (refer to Figure 39).

1.18 RIE the remaining silicon material within the fuel and oxidant inlet/outlets and the dicing lanes from the front side of the silicon substrate (refer to Figure 41).

1.20 Selectively diffusion dope the porous silicon with phosphorous – to make the porous silicon conductive, approximately 50 mΩ-cm.

1.21 Deposit photoresist patterned from Mask A1-5F on the front side of the silicon substrate – the openings only expose the area for the electrical contacts between the porous silicon and the dicing lanes (refer to Figures 43A and 43B).

1.22 RIE both dielectrics from the front side of the silicon substrate (refer to Figure 44).

1.23 Strip photoresists from the front side of the silicon substrate (refer to Figure 45).

1.24 Sputter 200 Å Ti-W followed by an additional 4,800 Å Au on the front side of the silicon substrate - for the electrical contacts between the porous silicon and the dicing lanes (refer to Figure 46).

1.25 Deposit photoresist patterned from Mask A1-6F on the front side of the silicon substrate – the photoresist covers the sputtered metal located on the front side of the substrate for negative metal lift off (refer to Figures 47A and 47B).

1.26 Etch Au and Etch Ti-W from the front side of the silicon substrate (refer to Figure 48).

1.27 Strip the photoresists from the front side of the silicon substrate (refer to Figure 49).

1.28 Remove the silicon nitride via RIE on both the front and backside of the silicon substrate (refer to Figure 50).

1.29 Evaporate 500Å of Ti-W followed by 2µm of Au onto the backside of the silicon substrate (refer to Figure 51).

1.30 Catalyst Deposition & Preparation: (a) Heat the silicon substrate to 200°C in air for 2 hours; (b) After the silicon substrate has cooled to RT, place silicon wafer in an aqueous ammonia solution of tetraamineplatinum(II) hydroxide hydrate, $[\text{Pt}(\text{NH}_3)_4](\text{OH})_2 \cdot x\text{H}_2\text{O}$, at pH 8.5 and stir for 10 hours. The solution will contain enough platinum complex to deposit a maximum of 2% weight platinum on silicon, *i.e.*, a 100 mg wafer will be placed in a bath containing 2 mg of platinum (3.4 mg tetraamineplatinum(II) hydroxide hydrate); (c) Remove the silicon wafer from the aqueous ammonia solution and dry *in vacuo* for 1 hour; (d) Heat silicon substrate under a flow of oxygen/nitrogen

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(20:80) from RT to 400°C at a rate of 2°C per minute, approximately 3 hours, and then hold at 400°C for 1 hour; (e) After the silicon wafer has cooled to RT, placed silicon wafer in an aqueous ammonia solution of hexamineruthenium(III) chloride, $[\text{Ru}(\text{NH}_3)_6]\text{Cl}_3$, at pH 8.5 and stir for 10 hours. The solution will contain enough ruthenium complex to deposit a maximum of 1.5% weight ruthenium on silicon, *i.e.*, a 100 mg wafer will be placed in a bath containing 1.5 mg ruthenium (4.6 mg hexamineruthenium(III) chloride); (f) Remove the silicon wafer from the aqueous ammonia solution and dry *in vacuo* for 1 hour; (g) Heat silicon substrate under a flow of oxygen/nitrogen (20:80) from RT to 400°C at a rate of 2°C per minute, approximately 3 hours, and then hold at 400°C for 1 hour; (h) Heat the silicon wafer under flowing hydrogen. The temperature should be rapidly increased from RT to 400°C at a rate of 25°C per minute, approximately 15 minutes, and held at 400°C for 4 hours (refer to Figure 52).

The completed anode structure manufactured in accordance with the above processing steps is illustrated in Figures 53A and 53B, respectively.

CATHODE FABRICATION - Start with a silicon substrate having the following characteristics: 400 μm double side polished, (100) crystal orientation, to 1.0 $\Omega\text{-cm}$, n-type, 100 mm diameter (refer to Figure 54), and process in accordance with the following steps:

2.1 Deposit a 1000 Å \pm 5% layer of Stoichiometric silicon nitride on the front and backside of the silicon substrate via LPCVD nitride deposition (refer to Figure 55).

2.2 Deposit photoresist patterned from mask C1-1B on the backside of the silicon substrate - to initially open inlet and outlet ports (refer to Figures 56A and 56B).

2.3 RIE silicon nitride on the silicon substrate backside (refer to Figure 57).

2.4 Isotropic or DRIE of 60-micron depth cavities from the backside of the silicon substrate – for the fuel and oxidant inlet/outlets and dicing lanes (refer to Figure 58).

5 2.5 Strip the photoresists off the backside of the silicon substrate (refer to Figure 59).

2.6 Remove all nitride on the backside of the silicon substrate by RIE (this fabrication step can be disregarded depending on stacking requirements) (refer to Figure 60).

10 2.7 Sputter or evaporate 1 μm of aluminum on the backside of the silicon substrate – the aluminum will serve as an Ohmic contact for anodic etching (refer to Figure 61).

2.8 Deposit photoresist patterned from Mask C1-2F on the front side of the silicon substrate – to open regions on the substrate for porous silicon etching (refer to Figures 62A and 62B).

15 2.9 RIE silicon nitride on the silicon substrate front side (refer to Figure 63).

2.10 Strip the photoresists from the front side of the silicon substrate (refer to Figure 64).

2.11 Anodic etch the silicon substrate – creating 50 μm porous silicon layer (refer to Figure 65).

20 2.12 Strip off aluminum contact from the backside of the silicon substrate (refer to Figure 66).

2.13 Selectively dope the porous silicon with phosphorus – to make the porous silicon conductive, approximately 50 $\text{m}\Omega\text{-cm}$.

25 2.14 Anneal substrate to in N_2 – to drive in dopant and relieve stress inside the silicon substrate.

2.15 Sputter or evaporate 1 to 3 μm of aluminum on the front side of the silicon substrate – the aluminum serves as a thermal conductive layer for DRIE (refer to Figure 67).

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2.16 Deposit photoresists patterned from mask C1-3B on the backside of the silicon substrate - to initially open inlet, outlet ports and porous silicon for DRIE, AZ4620, 12 μm (refer to Figures 68A and 68B).

2.17 Deep Reactive Ion Etching on the backside of the silicon substrate – anisotropic etching *i.e.*, Bosch Etch (refer to Figure 69).

2.18 Strip the photoresists off the backside of the silicon substrate (refer to Figure 70).

2.19 Strip off aluminum contact from the front side of the silicon substrate (refer to Figure 71).

2.20 Remove silicon nitride from the front side of the silicon substrate via RIE (refer to Figure 72).

2.21 Sputter a seed layer of palladium on the front side of the silicon substrate – to be used to electroplate palladium for MeOH blocker (refer to Figure 73).

2.22 Deposit photoresists patterned from mask C1-4F on the front side of the silicon substrate – to selectively deposit the palladium-blocking layer (refer to Figures 74A and 74B).

2.23 Pulse plate palladium as a MeOH blocking layer (refer to Figure 75).

2.24 Strip the photoresist off the front side of the silicon substrate (refer to Figure 76).

2.25 Deposit photoresists patterned from mask C1-5F on the front side of the silicon substrate and deposit photoresists to cover backside of the silicon substrate – to remove excess seed layer (refer to Figures 77A and 77B).

2.26 Remove excess palladium seed layer by chemical etch technique (refer to Figure 78).

2.27 Strip the photoresists off the front side and backside of the silicon substrate (refer to Figure 79).

2.28 Catalyst deposition and preparation: (a) Heat the silicon substrate to 200°C in air for 2 hours; (b) After the silicon substrate has cooled to RT, place silicon wafer in an aqueous ammonia solution of tetraamineplatinum(II) hydroxide hydrate, $[\text{Pt}(\text{NH}_3)_4](\text{OH})_2 \cdot x\text{H}_2\text{O}$, at pH 8.5 and stir for 10 hours. The

solution will contain enough platinum complex to deposit a maximum of 2% weight platinum on silicon, *i.e.*, a 100 mg wafer will be placed in a bath containing 2 mg of platinum (3.4 mg tetraamineplatinum(II) hydroxide hydrate); (c) Remove the silicon wafer from the aqueous ammonia solution and dry *in vacuo* for 1 hour; (d) Heat silicon substrate under a flow of oxygen/nitrogen (20:80) from RT to 400°C at a rate of 2°C per minute, approximately 3 hours, and then hold at 400°C for 1 hour; (e) Heat the silicon wafer under flowing 1% H₂ in N₂. The temperature should be rapidly increased from RT to 400°C at a rate of 25°C per minute, approximately 15 minutes, and held at 400°C for 4 hours.

The completed cathode structure manufactured in accordance with the above processing steps is illustrated in Figures 80A, 80B and 80C, respectively.

EXAMPLE 2

SOL-GEL DERIVED ELECTRODE STRUCTURES

This example discloses the processing steps associated with making a sol-gel-based electrode assembly adapted for use with a fuel cell system. In this example, the processing steps consist essentially of (1) the anode fabrication steps, and (2) the cathode fabrication steps. Without limitation, the principal processing steps are set forth below and with reference to Figures 81 to 153.

ANODE FABRICATION - Start with a silicon substrate having the following characteristics: (100) crystal orientation, 1 to 10 Ω-cm, n-type, 100 mm diameter, 300 +/- 2 μm double side polished prime (DSPP), TTV < 1 μm, and process in accordance with the following steps:

1.1 Grow 5000 Å, both sides of wet thermal oxide (SiO₂) on both sides of wafer. Deposit 600 Å, stoichiometric LPCVD silicon (Si₃N₄) on both sides of wafer (refer to Figure 81).

1.2 Spin on AZ 1512 photoresist (refer to Figure 82).

- 1.3 Expose with Photomask A2-1F-KOH1 for front side (refer to Figure 83).
- 1.4 RIE dielectrics on front side (refer to Figure 84).
- 1.5 Strip photoresist and clean wafer (refer to Figure 85).
- 1.6 KOH etch 100 μm in stirred 28% KOH, at 75°C (refer to Figure 86).
- 5 1.7 Grow 3000 Å wet thermal oxide, (SiO_2) on exposed Si regions (refer to Figure 87).
- 1.8 Deposit 600 Å of silicon nitride, Si_3N_4 (refer to Figure 88).
- 1.9 Spin on AZ4620 photoresist on front side (refer to Figure 89).
- 1.10 Expose with photo mask A2-2F-KOH2 for front side, which opens the
- 10 front side patterns for active region for sol-gel (refer to Figure 90).
- 1.11 RIE dielectrics down to bare Si on front side using CHF_3 and O_2 . Strip photoresist and clean wafer (refer to Figure 91).
- 1.12 KOH etch 100 μm in stirred 28% KOH, at 75°C (refer to Figure 92).
- 1.13 Use photo mask A2-3F-PSPAD on front side, with AZ4620, for
- 15 conductive strip (refer to Figure 93).
- 1.14 RIE dielectrics 500 μm in width using CHF_3 and O_2 on front side to make PS strip (refer to Figure 94).
- 1.15 Use photo mask A2-4B-OHMIC on back side with photoresist AZ1518 to create openings for ohmic contact for anodic etching (refer to Figure 95).
- 20 1.16 RIE dielectrics on back side to bare Si using CHF_3 and O_2 . Then strip photoresist and clean wafer (refer to Figure 96).
- 1.17 Evaporate 1 μm Al on backside for anodic etching ohmic contact (refer to Figure 97).
- 1.18 Anodic etch 50 μm (PS etch for macropores) in active region where sol-
- 25 gel will be cast (refer to Figure 98).
- 1.19 Wet etch Al (refer to Figure 99).
- 1.20 Cast sol-gel precursor solution (refer to Figure 100).
- 1.21 Heat treat at 120°C for 24 hours, pyrolyze at 450°C for 4 hours under flowing H_2 (refer to Figure 101).
- 30 1.22 Evaporate 1 μm Al on backside as an RIE mask (refer to Figure 102).

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1.23 Use photo mask A2-5B-RIE1 on back side with photoresist AZ4620, to create offset right feed port (refer to Figure 103).

1.24 Wet etch Al at port area on back side (refer to Figure 104).

5 1.25 RIE dielectrics using CHF_3 and O_2 on back side at port opening (refer to Figure 105).

1.26 RIE 100 μm Si on backside at port opening using SF_6 (refer to Figure 106).

1.27 Strip photoresist and clean wafer (refer to Figure 107).

10 1.28 Use photo mask A2-6B-DRIE on back side, with photoresist AZ4620, for DRIE shield (refer to Figure 108).

1.29 Wet etch Al at port area on back side (refer to Figure 109).

1.30 RIE dielectrics using CHF_3 and O_2 at port area on back side (refer to Figure 110).

1.31 DRIE to the dielectric interface on the front side (refer to Figure 111).

15 1.32 Strip photoresist and clean wafer (refer to Figure 112).

1.33 Use photo mask A2-7B-RIE2 with AZ4620 on the back side to expose Si for etching (refer to Figure 113).

1.34 Wet etch Al (refer to Figure 114).

20 1.35 RIE Si using CHF_3 and O_2 until porous silicon is reached, which is approximately 50 μm (refer to Figure 115).

1.36 Strip photoresist and clean wafer (refer to Figure 116).

1.37 Wet etch all Al (refer to Figure 117).

1.38 Use photo mask A2-8B-LIFTOFF1 on the back side with AZ4620, to provide conductive layer and bonding interface (refer to Figure 118).

25 1.39 RIE all of back side nitride (Si_3N_4) using CHF_3 and O_2 (refer to Figure 119).

1.40 Evaporate Ti adhesion layer for successive Au layer on the back side (refer to Figure 120).

1.41 Evaporate 2 μm of Au on back side (refer to Figure 121).

30 1.42 Ti-Au lift-off using acetone (refer to Figure 122).

1.43 Use photo mask A2-9F-LIFTOFF2 on the front side with AZ4620, to provide conductive layer and bonding interface (refer to Figure 123).

1.44 RIE dielectrics on front side using CHF_3 and O_2 (refer to Figure 124).

1.45 RIE dielectrics on front side (refer to Figure 125).

5 1.46 Evaporate Ti adhesion layer for successive Au layer on front side (refer to Figure 126).

1.47 Evaporate 2 μm of Au on front side (refer to Figure 127).

1.48 Front side Ti-A side Ti-Au lift-off using acetone (refer to Figure 128).

10 CATHODE FABRICATION - Start with a silicon substrate having the following characteristics: 300 μm double side polished, (100) crystal orientation, 1 to 1.0 $\Omega\text{-cm}$, n-type, 100 mm (4") diameter, and process in accordance with the following steps:

2.1 Nitride Deposition – 1000 Å, S1 (front side) and S2 (back side).

15 2.2 Photo Mask C2_1F_PS for front side, S1, using photoresist AZ1512 (refer to Figure 129).

2.3 Photo Mask C2_2B_OHMIC for backside, S2, using photoresist AZ1512 (refer to Figure 130).

2.4 RIE nitride both front and backside (refer to Figure 131).

20 2.5 Strip photo resists and clean wafer (refer to Figure 132).

2.6 Evaporate 1 μm of Al on backside, S2 (refer to Figure 133).

2.7 Isotropic etch: $\text{HF}:\text{HNO}_3:\text{CH}_3\text{COOH}$, etch out 200 μm Si (refer to Figure 134).

2.8 Anodic etch 50 μm porous structure on front side (refer to Figure 135).

25 2.9 Cast sol-gel precursor solution (refer to Figure 136).

2.10 Heat treat at 120°C for 24 hours (refer to Figure 137).

2.11 Pyrolyze at 500°C for 4 hours under flowing H_2 .

2.12 Spin on photoresist on front side, S1, using photoresist AZ4620 (refer to Figure 138).

30 2.13 Photo mask C2_3B_OFFSET, S2, using photoresist AZ4620.

- 2.14 Etch Al (refer to Figure 139).
- 2.15 RIE 100 μm with SF_6 (refer to Figure 140).
- 2.16 Photo Mask C2_4B_DRIE, S2, using photoresist AZ4620 (refer to Figure 141).
- 5 2.17 DRIE 200 μm (refer to Figure 142).
- 2.18 Strip photoresist on both sides, S1 and S2 (refer to Figure 143).
- 2.19 Strip Al (refer to Figure 144).
- 2.20 RIE nitride front side, S1 (refer to Figure 145).
- 2.21 Sputter Pd 2000 Å on the front side, S1 (refer to Figure 146).
- 10 2.22 Photo Mask C2_5F_PLATING (refer to Figure 147).
- 2.23 Pulse plate Pd thin film (refer to Figure 148).
- 2.24 Strip Photoresist and clean wafer (refer to Figure 149).
- 2.25 Photo Mask C2_6F_PDETCH (refer to Figure 150).
- 2.26 Etch Pd (refer to Figure 151).
- 15 2.27 RIE dielectrics on backside (if required for bonding) (refer to Figure 152).
- 2.28 Sputter external electrical connections on backside (if required for bonding) and (a) sputter 500 angstrom TiW and (b) Sputter 2 μm Au for metal connects (refer to Figure 153).

20 While the hydrodynamic fluid transport and flow channel passageways of the present invention have been described in the context of the embodiments illustrated and described herein, the invention may be embodied in other specific ways or in other specific forms without departing from its spirit or essential characteristics. Therefore, the described embodiments are to be considered in all respects as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended

25 claims rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

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